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**OPTIMAL CONTROLLER DESIGN
FOR THE MICROGRAVITY ISOLATION MOUNT (MIM)**

Prepared By: R. David Hampton, Ph.D., P.E.
Academic Rank: Assistant Professor
Institution and Department: McNeese State University
Engineering Department (Mechanical)

NASA/MSFC:

Team: Precision and Pointing Team
Branch: Flight Dynamics, Precision Pointing,
and Mechanical Systems Control Branch
Division: Guidance and Control Systems Division
Laboratory: Structures and Dynamics Laboratory

MSFC Colleague: Mark S. Whorton

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Introduction

Acceleration measurements on the U.S. Space Shuttle and the Russian Mir Space Station show acceleration environments that are noisier than expected (DeLombard et al., 1997). The acceleration environment on the International Space Station (ISS) will likewise not be as clean as originally anticipated; the ISS is unlikely to meet its microgravity requirements without the use of isolation systems (DeLombard et al., 1997, and System Specification (no author), 1995). While the quasi-static acceleration levels due to such factors as atmospheric drag, gravity gradient, and spacecraft rotations are of the order of several micro-g, the vibration levels above 0.01 Hz are likely to exceed 300 micro-grams, with peaks typically reaching milli-g levels (DelBasso, 1996). These acceleration levels are sufficient to cause significant disturbances to many science experiments that have fluid or vapor phases, including a large class of materials science experiments (Nelson, 1991).

The Microgravity Isolation Mount (MIM) is a six-degree-of-freedom (6-DOF) magnetic-levitation system which was designed by the Canadian Space Agency (CSA). Its purpose is to isolate experiments from the high-frequency (>0.01 Hz) vibrations on the Space Shuttle, Mir, and ISS, while passing the quasi-static (<0.01 Hz) accelerations to the experiment (Tryggvason, 1994). The performance limit depends primarily on the character of the umbilical required between the MIM base (stator) and the MIM flotor on which the experiment is mounted. The emphasis with the MIM design is on isolation at the experiment level, with isolation ideally accomplished on only the sensitive elements of an experiment; this limits the need for a heavy umbilical. In the current implementation, the umbilical provides power to experiments mounted on the flotor, along with data-acquisition and control services (Tryggvason et al., 1997).

The first MIM unit was launched in the Priroda laboratory module which docked with Mir in April 1996. The system has been operational on Mir since May 1996, and has supported several materials science experiments. An upgraded system (MIM II) will be flown on the U.S. Space Shuttle Discovery on mission STS-85 in August 1997.

MIM (both the original and the upgraded unit) consists of two major components: a fixed stator and a free flotor. The system includes eight wide-gap Lorentz-force (voice-coil) actuators with the magnets on the flotor and the current coils on the stator. By controlling the currents independently in each of the coils, full 6-DOF control is achieved of the flotor with respect to the stator. The system includes three light-emitting diodes (LEDs) imaged onto three position-sensing devices (PSDs) which together allow position tracking of the flotor, relative to the stator. The system also includes six accelerometers for monitoring the stator and flotor accelerations. (Only the flotor-mounted accelerometers are currently used for control.)

The control system used with MIM on Mir uses simple proportional-derivative (PD) control with relative position measurement to suspend the flotor as an equivalent spring-mass-damper system typically tuned for near-critical damping; acceleration feedback can be added to tune the system by increasing its effective mass. It is desired to improve the isolation capabilities of MIM by using various more sophisticated control approaches. One such approach, pursued by this investigator, is the application of H_2 controllers which use standard linear quadratic gaussian (LQG) theory augmented by appropriate frequency

weighting. H_2 controllers have the advantage of using a quadratic (rms) performance index, which measures performance in terms of an energy measurement (state covariance plus control covariance). This is a very reasonable performance measure for a microgravity isolation problem (Hampton et al., 1996; see Saberi et al, 1995, for a thorough discussion of H_2 theory). However, H_2 theory does not allow the “up-front” incorporation of stability-robustness- or performance demands into the controller design “machinery.” H_∞ synthesis and μ synthesis, on the other hand, allow such constraints to be placed directly on the controller in the design process; however, the performance measure that is used must be an infinity-norm (Stoorvogel, 1995). The newer mixed-norm theory allows the controls engineer to design a compensator that minimizes a 2-norm of the closed-loop transfer-function matrix from one set (vector) of plant inputs to a set of plant outputs, subject to an ∞ -norm constraint on the closed-loop transfer function from a second (not necessarily different) set of inputs to a second (again, not necessarily distinct) set of outputs (Whorton, 1997). This approach is a logical sequel to an H_2 (or H_∞/μ approach), and is expected to produce controllers superior to those achievable by either of the former methods.

Mixed-norm controller design

Mixed H_2/μ design can be achieved using the general procedure outlined below (Whorton, 1997). This is the procedure being applied to controller design for MIM.

1. *Develop a model for the H_2 problem.*
(The fundamental problem is typically an H_2 problem, because typically the performance measure is to be a quadratic (rms) measure. An initial H_2 controller, of the final desired order for the mixed H_2/μ controller, and satisfying the robust stability constraints, will be useful as a starting point for the H_∞ homotopy algorithm entered below at step 7.)
2. *Synthesize an H_2 (full-order) controller, with good nominal performance.*
(A full-order controller is needed because no direct path exists to synthesize a reduced-order controller with guaranteed stability.)
3. *Develop an uncertainty model for robust stability analysis.*
4. *Form the generalized plant for mixed-norm design.*
5. *Reduce the control authority to result in a full-order H_2 controller which satisfies robust stability (at the expense of some nominal performance).*
(Low-authority control is needed because order-reduction techniques tend to work best for low-authority. Within the limits imposed by order reduction and robust stability, the loss of performance will be recovered via mixed-norm H_2/μ homotopy, i.e., alternating homotopies on ρ and λ , with γ fixed at unity.)
6. *Reduce the full-order controller to the desired order. (Reduction in controller order may result in loss of closed-loop stability. Consequently, it may be necessary to reduce the control authority before order reduction in order to ensure closed-loop system stability.)*
(A controller of reduced order is needed to provide a starting point for the fixed-order mixed H_2/μ controller to be developed by H_∞ homotopy.)

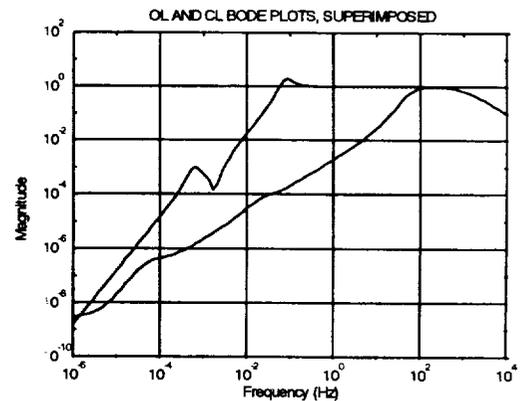
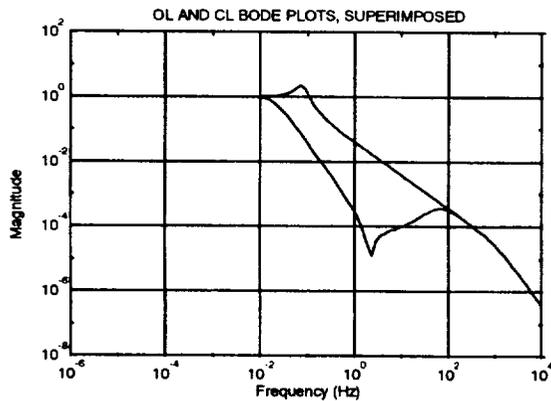
[NOTE: At this point a reduced-order H_2 controller will have been obtained which satisfies robust stability, but has suffered a loss in nominal performance in order to satisfy robust stability and closed-loop stability after the order-reduction step.]

7. *Transform the controller into canonical form.*
(The canonical form is needed to minimize the number of free parameters, in order (1) to produce a unique solution, and (2) to produce a static feedback-gain form of the five first-order equations expressing the necessary conditions for nominal performance and robust stability.)
8. *Fix γ (at $\gamma = 1$) and ρ , and perform a homotopy on λ until the closed-loop system H_2 -norm $\left(\|T_{z,w_r}\|_2\right)$ reaches a minimum or the closed-loop system H_∞ -norm $\left(\|T_{z,w_i}\|_\infty\right)$ approaches unity.*
9. *Compute the μ -measure $\left(\|T_{z,w_r}\|_\mu\right)$. If it is appreciably less than one, compute and approximate the optimal D -scales, absorb them into the plant, and continue with the homotopy on λ until the robust stability (unit) boundary is reached again. Repeat as necessary to obtain a controller $G(\rho, \lambda, \gamma)$ for which the μ -measure is unity.*
(At this point the controller-gain matrix $G(\rho, \lambda, \gamma)$ will have been found which places the closed-loop system on the robust-stability “boundary” for the given value of ρ and the assumed plant and uncertainty models. In effect, λ -homotopy has been used to solve the five matrix equations expressing the first-order sufficient conditions for nominal performance and robust stability, for the given value of ρ .)
10. *With γ fixed at a value of one, and λ fixed at the value determined above, perform a homotopy on ρ to increase the control authority (by decreasing ρ).*
11. *Repeat steps 8 through 10 to obtain a set of controller feedback gains G as a function of decreasing ρ (increasing control authority). These gains all yield nominal performance, for the given value of ρ , while ensuring robust stability. The value of ρ can be decreased in this fashion either until $G(\rho)$ yields the desired closed-loop nominal performance, in terms of the H_2 norm $\left(\|T_{z,w_r}\|_2\right)$, or until no further decrease in ρ is possible without sacrificing robust stability.*

Effectively, what is done in the above process is iteratively to use homotopy on ρ and homotopy on λ to solve the five first-order necessary conditions for nominal stability and robust performance in terms of the chosen plant, disturbance, and uncertainty models, design frequency weights, and tuning parameter ρ . This yields a set of fixed-order controllers $G(\rho)$ that can be evaluated, for decreasing values of ρ , until a satisfactory (or until the best achievable) nominal performance has been obtained.

Current Status

A dynamic model of MIM II (Hampton et al., 1997) was created in Matlab, and used (with appropriately-selected frequency weightings) to develop three full-order and six reduced-order high-authority, high performance H_2 controllers. The controllers were spot-checked for robust performance and robust stability using Monte Carlo methods. Simulations by CSA indicate the controller performance to be as predicted, and they have been installed on MIM II for testing on STS-85. The first figure below shows the predicted open- and closed-loop transmissibilities, for a typical controller, from stator acceleration disturbances through umbilical to flotor acceleration, with both accelerations directed along the axis of one of the flotor accelerometers. (The plots are very similar for the other flotor accelerometer directions.) The second figure shows the predicted closed-loop transmissibilities, for the same controller and in the same direction, due to acceleration disturbances applied directly to the flotor. (The lower curve in each figure is the closed-loop curve.) Note that both types of disturbance experience significant attenuation in the 0.01 Hz to 10 Hz frequency range. As indicated by the first figure, the indirect (umbilical-induced) disturbances must be simply transmitted without attenuation in the range below 0.01 Hz, due to rattlepace constraints.



A modal uncertainty model was developed for the MIM and implemented in a Simulink model suitable for mixed-norm controller design.

Conclusion and Future Work

H_2 controllers, when designed using an appropriate design model and carefully chosen frequency weightings, appear to provide robust performance and robust stability for MIM. The STS-85 flight data will be used to evaluate the H_2 controllers' performance on the actual hardware under working conditions. Next, full-order H_∞ controllers will be developed, as an intermediate step, in order to determine appropriate H_∞ performance weights for use in the mixed-norm design. Finally the basic procedure outlined above will be used to develop fixed-order mixed-norm controllers for MIM.

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